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This report describes progress toward understanding and quantifying injury arising from impact or impulsive loading to the body from blast, projectiles, or vehicle restraint systems.

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# Contents

# 1. Introduction

## 1.1 Background

In the course of training, the soldier is exposed to a variety of blast sources (small and large caliber), in a variety of surroundings (in the open and inside enclosures), and for single and multiple rounds. The Surgeon General of the Army must set conditions that limit the exposure of troops to blast overpressure (or "weapon noise") that will result in only a very small incidence of deleterious effects in the soldier population.

Military Standard 1474C (1991) provides rules for determining exposure limits based on auditory hazard. The data used to formulate these limits came from small caliber (high frequency) fire. The Standard assumes that the blast field can be characterized by two parameters: the peak pressure and a time duration. Based on those two quantities, a maximum number of exposures are determined. If the combination of quantities exceeds the "Z-line," the Standard allows no exposures because of unspecified nonauditory danger.

When an exposure exceeds the Standard's nonauditory limits, man-rating studies must be conducted to establish exposure limits on a weapon-by-weapon basis. This is a time-consuming and expensive procedure that is likely to become more and more common as weapon power increases. Furthermore, when the blast overpressure hazard arises in an enclosure, the variation and permutations of the exposure become so enormous that case-by-case studies are not feasible.

When blast overpressure levels increase further, the concern switches from identifying threshold to anticipating soldier performance and effectiveness. Here, the guidance for Army doctrine has come from animal tests, largely concerned with lethality estimates. More recent animal tests and more thorough analysis of previous test data reveals that physiological effects are present at much lower values than had been previously thought and involve all of the body's air-containing organs.

Finally, animal studies that consider the effects of combined trauma have shown that the pathophysiological consequences can be profound, and could have implications both for the individual and for the medical care system. Once again, the elements entering such estimates do not properly reflect what is known about the physiological consequences of blast overpressure, nor is enough known to be able to confidently anticipate the consequences.

## 1.2 Previous Work

*Animal Tests.* Over the past 15 years, tests have been conducted at the Albuquerque Overpressure Test Site, under the sponsorship of the US Army Medical Research & Materiel Command (MRMC), exposing animals to blast loading. See Richmond, et al (1982), Dodd, et al., (1985), Yelverton, et al., (1993a), and Yelverton, et al., (1993b). Configurations included explosives detonated in the open and in enclosures and simulations of weapons fired from enclosures. The tests were conducted as studies with specific, narrow goals and the results were not systematically organized and analyzed in total.

Much of the experimental design was based on the assumption that respiratory injury had the lowest threshold and that injury to the upper respiratory tract preceded injury to the lung. An analysis of threshold injury levels, however, based on a preliminary compilation of the animal data showed an unexpected prevalence of injury to the gastrointestinal tract (GI) and no significant difference in threshold between any of the air-containing organs. See Stuhmiller (1990).

*Injury Mechanisms.* Since the lung had been identified initially as the most critical major organ injured by blast overpressure, work was conducted to understand the mechanical properties of lung materials, so that models could be constructed. See Fung, et al., (1985). In addition, a theory was advanced connecting tissue damage to the compression wave within the lung. Fung, et al., (1988).

Using the knowledge of the biological material properties, a mechanical model of the thorax wall and lung parenchyma was developed (Yu, 1990). These studies elucidated the reasons why pressure measurements differ between the large airways and the parenchyma. Furthermore, a linear relation was observed between the velocity of the chest wall and the strength of the internal compression wave. This pivotal finding was also confirmed with mathematical simulations (Vander Vorst and Stuhmiller, 1990).

As concern over GI tract injury grew, exploratory work was undertaken to identify the underlying mechanisms. Surrogate models revealed that damage to the tract arises from concentrations of stress at locations near air bubbles (Vasel, et al., 1990). Once the mechanism was understood, the mechanical properties controlling this phenomena could be identified and experiments conducted to determine the values of these properties in small animal intestines (Yu and Vasel, 1990). A surgical procedure was developed for an isolated, perfused model of the rabbit gut in which systematic studies could be conducted (Yu, et al., 1991).

*Mathematical Modeling.* The first biomechanical models to predict response to blast overpressure were developed by White, et al., (1971). The model was calibrated to predict

the esophageal pressure observed in large animal tests, but attempts to correlate this quantity with lethality were unsuccessful. Later, Josephson et al., revisited the model and concluded that the predicted pressures could not be correlated with injury. Stuhmiller (1986) showed that the empirical correlation of injury with hyperbolic curves on a peak pressure-duration axes are related to the amount of irreversible energy loss in mass-spring-damper systems. These "generic" models formed a theoretical basis from which current biomechanical models, such as Viano and Lau (1988) have been developed.

The first systematic application of this biomechanical approach was made for the tympanic membrane (Stuhmiller, 1989). Finite element modeling was used to transform the geometric details of the membrane and support structures into a mass-spring-damper system. Rupture of the membrane was associated with exceeding the tensile strength of the membrane fibers. The resulting model provided an excellent correlation of observed tympanic membrane rupture in isolated specimens. A summary of the biomechanical modeling approach and its potential for blast overpressure related problems is found in Stuhmiller, et al., (1990).

*Hazard Assessment.* As mentioned earlier, the military standard for occupational exposure is primarily one for auditory effects. A nonauditory limit was proposed that is a parallel curve with peak pressures increased by about a factor of 2. For combat casualty purposes, a lethality criteria was developed by Bowen empirically based on animal data. A "threshold" injury curve was proposed that is a parallel curve with peak pressures reduced by a constant factor. Subsequent data analysis has shown that injury occurs at peak pressures less than these "threshold" estimates.

To provide a better criterion, Dodd, et al., (1990) proposed a peak pressure-duration curve to define conditions that would not produce "unacceptable" injury (any injury to the lung or GI tract or more serious injury to the upper respiratory tract (URT)). Separate curves were developed for multiple exposures. These relations have been used by MRMC as an interim criterion for making health hazards assessment of free-field weapon exposures.

All of the relations based on peak pressure and duration become unreliable in enclosures because reverberations make the duration so long that extreme injuries are always predicted. Attempts to find "equivalent" free-field waveforms are scientifically unjustified and have produced equally unreliable results. Consequently, MRMC began to experiment with using Jaycor's "generic" models to assess complex wave exposures.

In addition, the complex nature of blast waves in enclosures produces pressure traces that differ significantly from one location to another (because of the additions and cancellations caused by the myriad of wall reflections). The traces at a particular location also differ significantly depending on whether an animal is present or not (because of the

shielding and amplifying effects of the body). These variations are further confounded by the shot-to-shot variations seen in repeated tests.

### 1.3 Open Issues

Despite the considerable number of animal tests that have been conducted and the progress made in understanding the origin and mechanisms of damage, there are still questions that must be answered in order to obtain a satisfying and reliable assessment of hazard. First, in order to focus research effort, it is necessary to determine which organs are most susceptible, how severity increases with blast strength, and what aspects of blast correlate with these injuries. Second, since each new weapon produces a seemingly different blast signature, it is necessary to find a unifying approach that will anticipate and interpret new environments. Third, in order to determine the limits of biomechanical modeling to predict injury, a full validation of a single model must be made against all of the observed data. Finally, in order for the research to impact occupational exposure standards, a methodology is needed for making health hazards assessment that provides an estimate of population effects and provides an estimate of error.

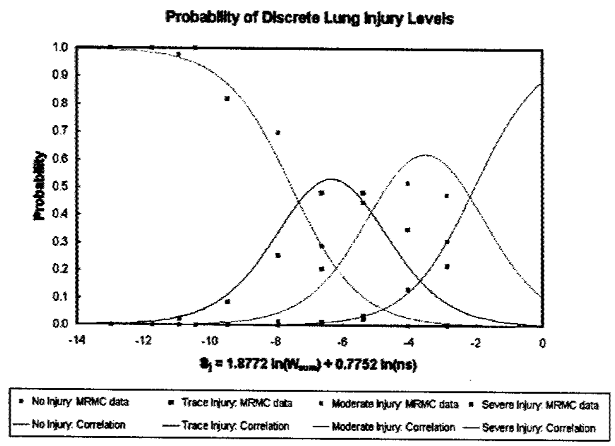
### 1.4 Objectives of Work

To address these issues, four objectives were set for the work. The first is to organize all of the animal data that has been collected at the Blast Overpressure Test Site in a form that can be used to determine the susceptibility of all organ systems to blast overpressure. The second is to evaluate computational fluid dynamics (CFD) as a unified approach to predicting and interpreting blast in complex geometries. The third is to develop and validate a biomechanically-based, predictive model of gross lung injury that can be applied in all blast environments. The final objective is to develop a methodology for assessing hazard that provides an estimate of risk to the population, including estimates of confidence based on the statistical uncertainties of the animal data and of pressure measurements.

# 2. Blast Overpressure

## 2.1 Multi-Outcome Logistic Analysis

Logistic analysis leading to a suitable correlate for contusive lung injury due to air blast is an important first step in establishing criterion to be used in nonauditory health hazard assessments. In the various experimental studies of sheep exposed to blast over-pressure in the free-field and in confined enclosures at the Blast Test Site, four distinct levels of injury were considered: trace (added in 1985), slight, moderate, and severe lung injury. An earlier statistical analysis of all available test data considered four separate dichotomous variables, each applying to the occurrence of an injury at or exceeding one of the specified levels of trauma. The probability of each injury level was described in terms of a logistic regression derived independently of outcomes for the other injury levels. It was determined that an inherent difficulty with this uncoupled approach is that it can lead to inconsistent and aphysical trends relative to adjacent levels of injury. For example, at some very low value of risk factor, the probability of slight or greater injury can exceed the probability of trace or greater injury. Even though each individual correlation might appear to fit well to the measured data, there is no guarantee that predicted outcomes will be self-consistent among all injury levels. In order to overcome this model deficiency, an "ordered" logit model (described in Greene, 1997, and in the STATA code manual) was employed in a multiple-outcome regression analysis. This statistical model is most appropriate for a correlation describing ordered multiple outcomes. Goodness-of-fit to the observed injury data was assessed by comparing measured cumulative injury counts to predicted counts. The agreement was deemed as quite good to excellent. The ordered logit model is employed in the final product, the INJURY 7.1 computer code for nonauditory HHA.

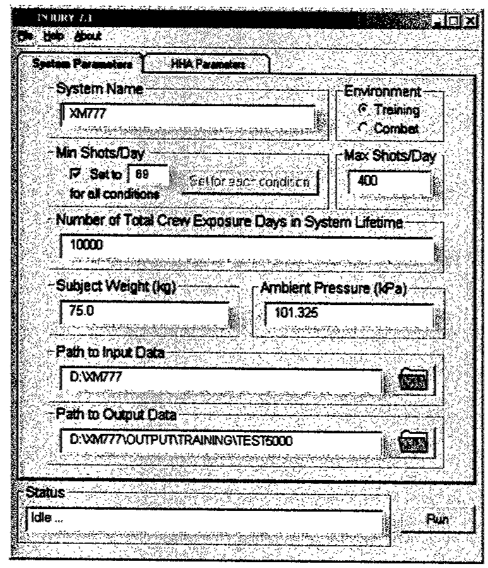



*Product 1. Masiello, Paul J. and Stuhmiller, James H. (2001). "Lung Injury Criteria for Air Blast Trauma," Jaycor Report J2997.24-01-158.*

*Product 2. Injury 7.1 Computer Code for Non-Auditory Health Hazard Assessment, Jaycor, Release date December 20, 2001.*

## 2.2 INJURY 7.1

The INJURY computer code is a product developed by Jaycor under the sponsorship of MRMC, filling the need for a standardized tool for performing nonauditory health hazard assessments (HHA). Presently, INJURY 7.1 addresses the contusive lung injury arising from repeated exposure to air blast. It is anticipated that this code will be widely used by CHPPM, to assist in their ongoing mission of HHA relative to existing and emerging weapon systems. Earlier versions of INJURY differ in several respects from the INJURY 7.1 code developed in FY02. A fundamental difference is that prior versions did not employ the ordered logit regression model, which was implemented and qualified during FY02. This model provides an improved level of consistency with observed animal injury data among all levels of injury. Another major improvement is that all BOP trace data can now be specified with a minimum of effort, saving a great deal of labor. This is achieved by assuming a test data directory structure following a known convention. In light of the possibility of dealing with literally thousands of traces, the previous method of manually specifying each BOP trace proved impractical. A standardized format for the directory structure of BOP test data allows simultaneous processing of all test data for a given study in a single step. INJURY 7.1 helps to automate the process of nonauditory HHA by requiring a minimum of user input, and reasonable execution times. Most weapon systems can be evaluated by INJURY 7.1 in only tens of minutes.



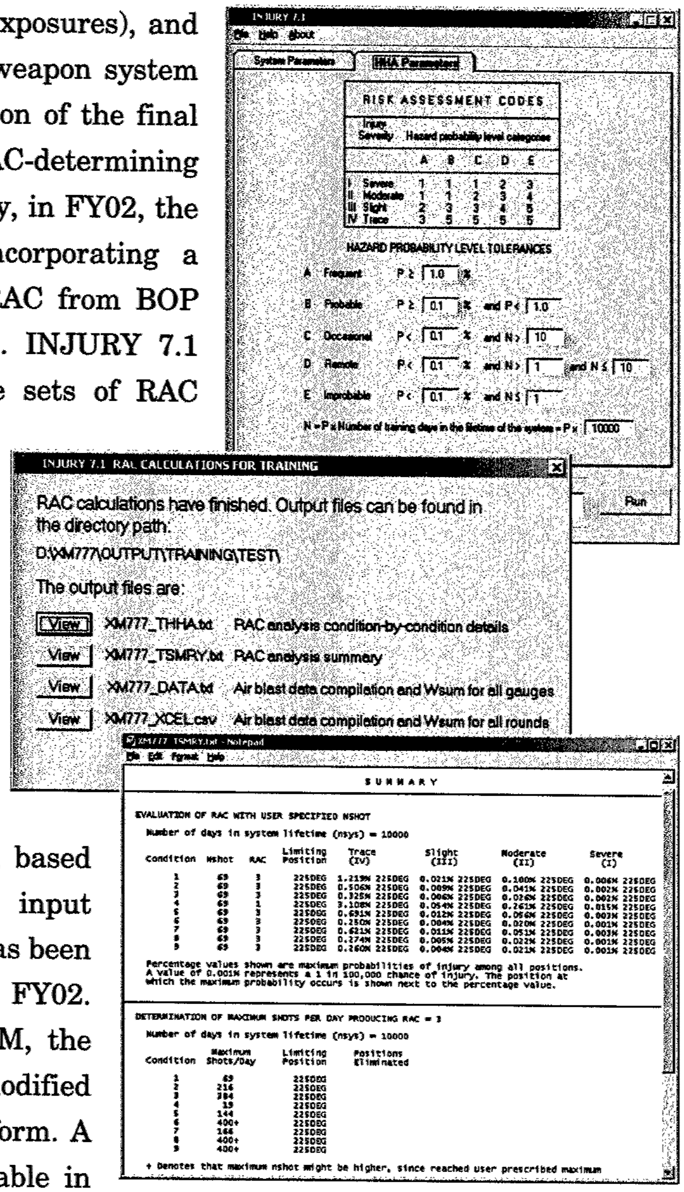

Perhaps the most significant difference of INJURY 7.1 relative to earlier versions of INJURY is the calculation of Risk Assessment Codes (RAC). The values of RAC output by INJURY 7.1 will enable a weapons program manager to make a rapid intelligent decision concerning the occupational safety of a given weapon system. Further details of the RAC capability in INJURY 7.1 are provided in Section 2.3.

INJURY 7.1 was released in December 2001, and is currently in use at CHPPM. Since the release date, INJURY 7.1 has been utilized by CHPPM for nonauditory HHA of several weapon systems (see Section 2.4 for further details).

*Product 3. Injury 7.1 Computer Code for Non-Auditory Health Hazard Assessment, Jaycor, Release date December 20, 2001.*

## 2.3 Risk Assessment Code (RAC) Automation

In earlier transition of Jaycor's INJURY software to CHPPM, it became apparent that an important and ultimate requirement of a complete analysis tool for nonauditory HHA is the determination of a Risk Assessment Code (RAC). Values of RAC depend on both the hazard severity and expected hazard frequency (e.g., number of repeated exposures to air blast in a single day, and lifetime exposures), and determine ultimately whether a given weapon system poses an acceptable HHA risk. Transition of the final product could not occur until a RAC-determining methodology was provided. Consequently, in FY02, the INJURY 7.1 code was developed, incorporating a determination of a minimum system RAC from BOP test data for a given weapons system. INJURY 7.1 provides output data for two separate sets of RAC computations. In the first set, the minimum RAC corresponding to the desired number of shots per day is output. In the second, the maximum possible number of shots per day based on a minimum allowable system RAC of 3 is displayed.




An additional feature is that INJURY 7.1 maintains separate output files for combat and training scenarios, based on separate runs with appropriate input parameters for each case. INJURY 7.1 has been distributed to and used by CHPPM in FY02. After feedback is received from CHPPM, the code methodology and software will be modified as necessary, and documented in final form. A commercial-grade Help facility is available in INJURY 7.1, describing RAC computations and including detailed instructions on the use of the code. This feature should prove useful prior to completion of a User Manual.

*Product 4. Injury 7.1 Computer Code for Nonauditory Health Hazard Assessment, Jaycor, Release date December 20, 2001.*

## 2.4 HHA Support

Jaycor has provided consulting services during FY02 to CHPPM staff, in their transition to automate nonauditory Health Hazard Assessment (HHA) using the INJURY 7.1 computer code. In the course of this work, Jaycor has performed independent HHA's of the following weapon systems:

(1) AT4CS: Anti-tank weapon

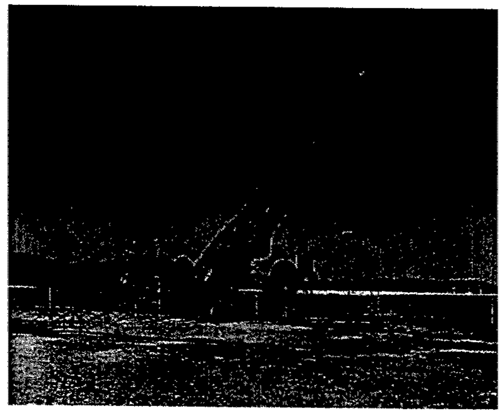
(2) BDM: Bunker Defeating Munition

(3) M109A6 w/FAASV: Paladin tank towing FAASV

(4) M109A5/6: Paladin untowed

(5) M84: Stun Grenade

(6) XM777: Light Weight Howitzer



**XM777 Light Weight Howitzer**

For most of these weapon systems, CHPPM was provided with Jaycor code output for comparison with CHPPM output of INJURY 7.1. Any discrepancies were noted and resolved by interaction with CHPPM staff. As part of this effort, Jaycor collected and assembled the necessary BOP test data, then assisted CHPPM in determining suitable values for required input parameters, and in renaming and restructuring BOP trace files for compatibility with INJURY 7.1.

*Product 5. Injury 7.1 Computer Code for Non-Auditory Health Hazard Assessment, Jaycor, Release date December 20, 2001.*

*Product 6. Non-Auditory Health Hazard Assessment Reports for Weapon Systems: AT4CS, BDM, M109A6, M84, M109A6 w / FAASV; Jaycor, Paul J. Masiello, 2001.*

# 3. Nonlethal Weapons

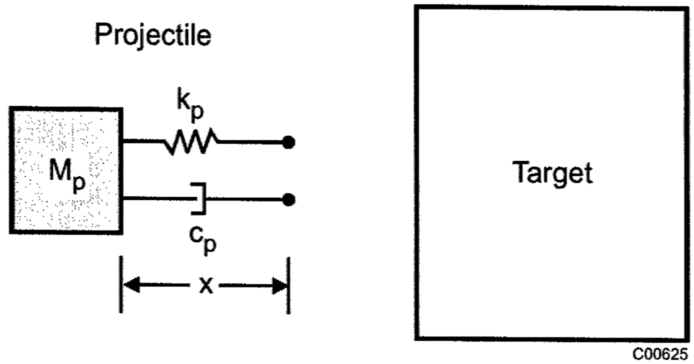
## 3.1 Deformable Projectile Model

The ITBM version 1.0 makes the assumption that the impact force is constant during the impact. It also requires the user to supply the values of two parameters, the duration and the momentum transfer of the impact which must be estimated with quasi-static guidance. It also assumes that the same force applies to all parts of the body impacted. In order to eliminate these shortcomings, we developed a nonlinear mass-spring-damper model for the nonlethal projectiles that consists of a crushable rubber part. The parameters involved are the force and damping coefficients that are basic properties of the projectile and can be determined by the performance of simple tests. The mass-spring-damper model of the projectile can then be combined with the existing biomechanical models for different parts of the body to make injury assessments. We validate this model by comparing with data obtained by high velocity impacts on surrogate target materials.

- Mass $M_p$
- Nonlinear spring

  $K_p x = k_{0p} x/(1 - |x|/D)^n$
- Nonlinear damper

  $c_p v = c_{0p} |x| v/D$

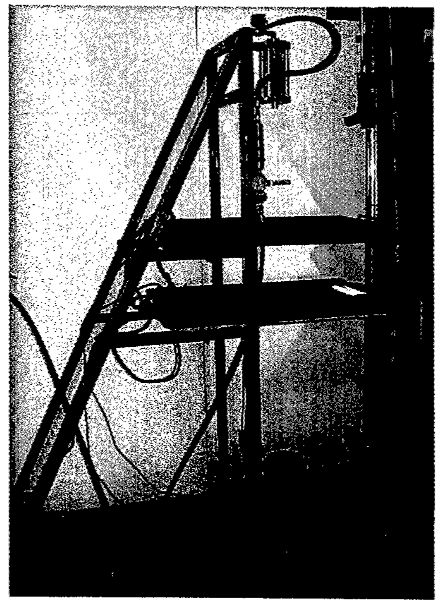



**The nonlethal weapon projectile with a rubber or plastic crushable part is model by a nonlinear mass-spring-damper system.**

*Product 7. Kan, K.-K., and J. H. Stuhmiller (2001). "Improvement of ITBM, Task I: Impact Characterization," Presentation to Joint Nonlethal Weapon Directorate February 13, 2001.*

## 3.2 Projectile Characterization Tests

The nonlethal weapon projectiles are characterized through a static compression test and a dynamic impact test. In the static compression test, a compression sensor is used to obtain a compression-load response that in turn determines the force coefficient for the spring. In the impact test, the projectile is launched at its operation velocity and bounced against a rigid steel plate. The rebound velocity in this test will determine the damping coefficient for the nonlinear mass-spring-damper model. We have validated this characterization method with compliant surrogate materials. The impact apparatus is available for characterization of new NLW projectiles.



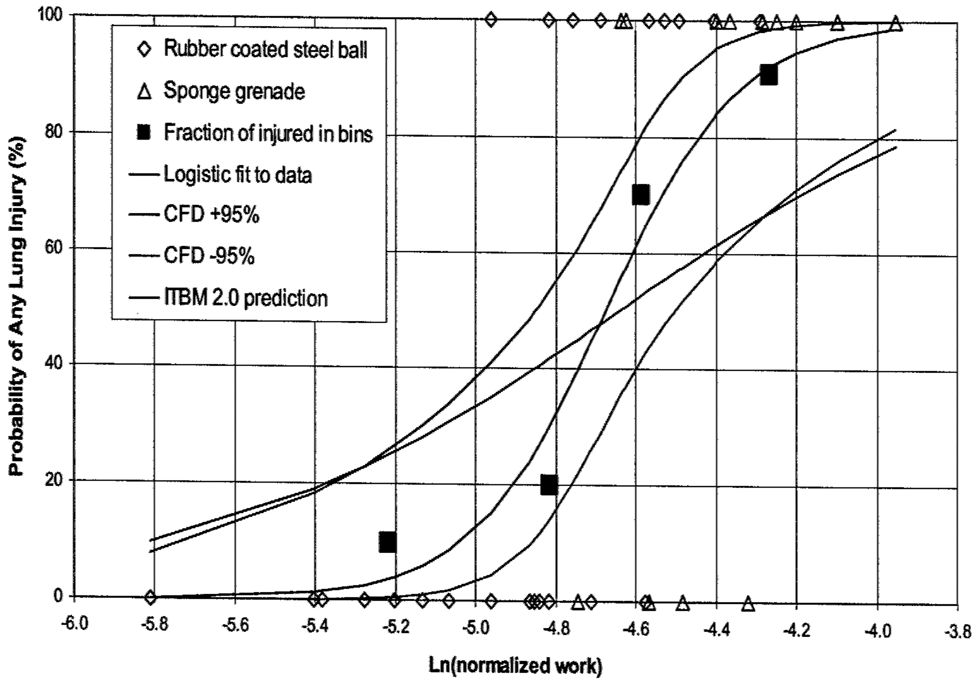
**This impact apparatus is constructed to launch NLW projectiles at their operation velocities. It is available for characterization of new NLW projectiles.**

*Product 8. Kan, K.-K., K. H. Ho, and J. H. Stuhmiller (2001). "Improvement of ITBM, Task I: Impact Characterization," Jaycor Report J2997.42-00-130.*

## 3.3 ITBM 2.0 Release

The new features in ITBM version 2.0 include the nonlinear mass-spring-damper model of the projectile, the multi-degree-of-freedom model of the thorax, and the effects of multiple impacts. The feature of multiple impact is implemented to be a direct simulation of the impacts with multiple projectiles. The effects of the body mass and the localization of the impact is considered by scaling. The model is calibrated by the animal tests recently completed by the Walter Reed Army Institute of Research.

A program CALIBRATE is also released for the calculation of the force and damping parameters for NLW projectiles.




**ITBM 2.0 is calibrated against the animal data obtained by WRAIR. The probability of lung injury is consistent with the results derived in BOP studies, showing that the normalized work is the correct predictor of this injury. Other predictors such as the viscous criterion were seen to be unsuitable for liver laceration and rib fracture.**

*Product 9. ITBM Version 2.0 Software (2001).*

*Product 10. Kan, K.-K., and J. H. Stuhmiller (2001). "ITBM Version 2.0," Jaycor Report J2997.43-00-156.*

*Product 11. Kan, K.-K. (2001). "(Interim) Total Body Model---Status and Injury Assessment," Jaycor Presentation Presented to Advanced Kinetic Modeling Human Effects Advisory Panel March 13-14, 2002.*

### 3.4 Population Effects

Model parameters, such as the mass, dimensions and force constants are developed for three additional segments of the population in ITBM. These segments are the adult female, ten year old child and six year old child. The two child categories are not subdivided by sexes. As in the case of adult male, we use the 50th percentile as the standards in all of the categories. However, subjects of different weights can be input into the model to obtain assessments for nonstandard subjects. The body, head and torso weights were obtained from the specifications of the Hybrid III dummies, although there is only the 5th percentile female dummy in the Hybrid III family. We obtained the body weight (65.5 kg) of the 50th

percentile women from the website of National Center for Health Statistics. The head and torso weights of the 50th percentile women were then scaled from the 5th percentile female dummy according to the body weight ratio. We assumed the ratio of the spine mass to the torso mass as a constant. By using the value of this ratio from the 50 percentile male, we then obtained the spine mass $m_S$ for different segments of the population. Other parameters in the chest model are scaled from the scaling rule as employed in ITBM 2.0.

**Body parameters for various segments of the population were developed for use in ITBM**

| Parameters | Units | Male | Female | 10 Year Old | 6 Year Old |
|---|---|---|---|---|---|
| Weight | kg | 77.7 | 65.5 | 34.5 | 23.4 |
| $m_H$ | kg | 4.5 | 3.83 | 3.66 | 3.47 |
| $R_H$ | m | 0.105 | 0.102 | 0.096 | 0.089 |
| $m_{sk}$ | kg | 0.0045 | 0.0042 | 0.0033 | 0.0030 |
| $m_{ch}$ | kg | 0.45 | 0.425 | 0.333 | 0.299 |
| $m_S$ | kg | 27.2 | 22.84 | 10.99 | 7.98 |
| $k_{12}$ | N/m | 281000 | 265133 | 207823 | 186779 |
| $k_{23}$ | N/m | 26300 | 24815 | 19451 | 17481 |
| $k_{23i}$ | N/m | 52600 | 49630 | 38902 | 34963 |
| $k_{ve23}$ | N/m | 13200 | 12455 | 9763 | 8774 |
| $c_{12}$ | N-s/m | 7.8 | 7.36 | 5.77 | 5.18 |
| $c_{23}$ (compression) | N-s/m | 520 | 491 | 385 | 346 |
| $c_{23}$ (extension) | N-s/m | 1230 | 1161 | 910 | 818 |
| $c_{ve23}$ | N-s/m | 180 | 170 | 133 | 120 |
| d | m | 0.0381 | 0.0359 | 0.0282 | 0.0253 |
| $A_f$ | $m^2$ | 0.0095 | 0.0095 | 0.00950 | 0.0095 |
| $V_{Lung}$ | $m^3$ | 0.0042 | 0.0035 | 0.0017 | 0.0012 |
| $L_{Lung}$ | m | 0.229 | 0.216 | 0.169 | 0.152 |
| $L_A$ | m | 0.22 | 0.208 | 0.163 | 0.146 |
| $k_A$ | N/m | 1.00E+05 | 9.44E+04 | 7.40E+04 | 6.65E+04 |
| $m_B$ | kg | 3.375 | 2.834 | 1.364 | 0.990 |
| $k_B$ | N/m | 1.73E+06 | 1.54E+06 | 9.48E+05 | 7.66E+05 |

*Product 12. Kan, K.-K., and J. H. Stuhmiller (2002). "ITBM Version 2.2," Jaycor Report J2997.47-02-175.*

### 3.5 Clothing Effects

Clothing effects were studied by launching of the NLW projectiles on a target that was covered with various clothing materials. The force of impact was recorded by a force gauge and the area of impact was recorded by TekScan instrumentation and pressure sensitive films. The clothing materials include common dress shirt (light), sweater (medium), sport jacket (heavy), and soft body armor patch. For the projectiles and the velocities tested, we did not see any significant difference in the force-time histories among different clothing materials. The tests showed increased area of impact for the heavy clothing and for the soft body armor. However, more tests are needed to draw a conclusion and to develop an analytical model that can be used in ITBM.

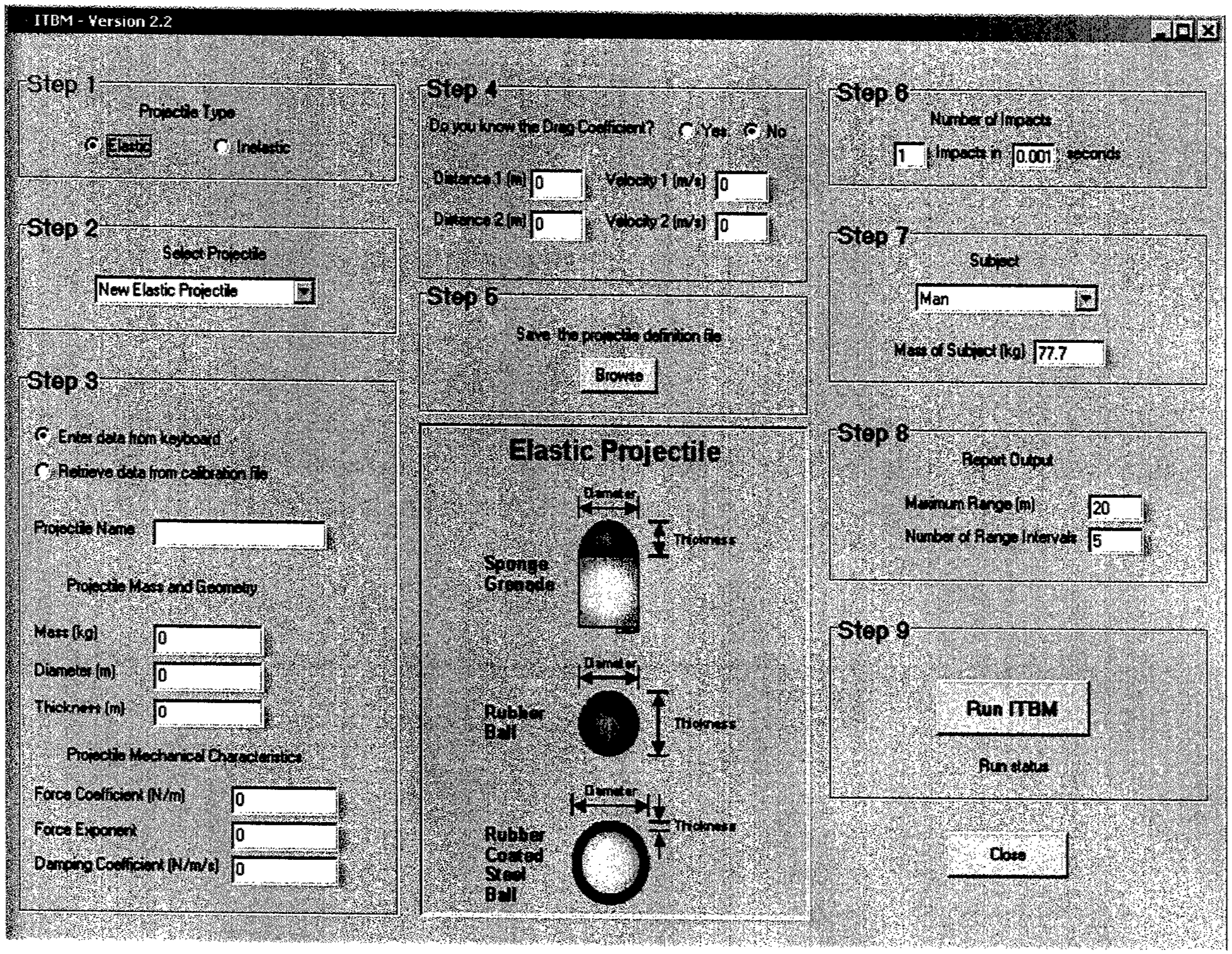
| Projectile | Normalized radius of impact | | |
|---|---|---|---|
| | No clothing | Heavy clothing | Soft armor |
| Sponge grenade | 1 | 1.06 | 1.13 |
| Rubber coated steel ball | 1 | 1.05 | 1.45 |

**Pressure sensitive film and TekScan results showed the effect of clothing in enlarging the area of impact. This enlargement of the area will lead to smaller probability of injury as predicted by ITBM.**

*Product 13. Stuhmiller J. H, K.-K. Kan, M, J, Vander Vorst, and K. H. Ho (2002). "Review of Total Body Modeling for Kinetic Nonlethal Weapons," Jaycor Presentation 2997-46/8-30-01.*

### 3.6 ITBM 2.2 Release

The ITBM version 2.2 includes the characteristics of four segments of the population, namely, man, woman, 12 year old child, and 6 year old child. Subjects of different weights are treated with their parameters scaled against the standard weights in the specific segments of the population. In this version, we also developed a systematic way of creating projectile files by the CALIBRATION module and later retrieved by ITBM in assessment analysis. A new user interface was developed for easier use of the program.




**ITBM 2.2 software has improved interface that guides the user through the steps of inputting the necessary parameters. The choice of the subject categories, i.e., man, woman, child age 12, and child age 6, in Step 7 is a new feature in this version.**

*Product 14. ITBM 2.2 Software (2002).*

*Product 15. Kan, K.-K., and J. H. Stuhmiller (2002). "ITBM Version 2.2," Jaycor Report J2997.47-02-175.*

## 3.7 Support of TERA

*Product 16. Kan, K.-K (2001). "Interim Total Body Model," Presentation at Risk Characterization for Nonlethal Weapon Workshop, Kingsgate Conference Center, University of Cincinnati, Cincinnati, Ohio, May 16, 2001.*

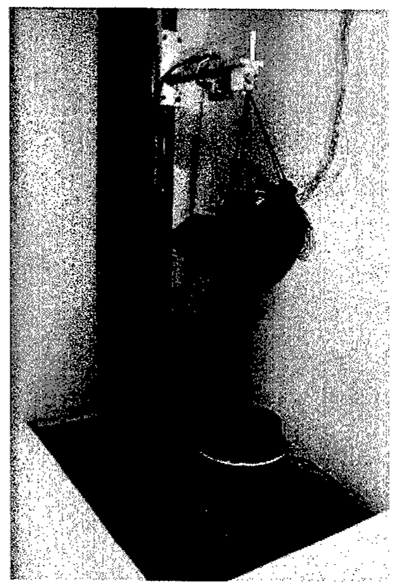
*Product 17. Stuhmiller, James H. (2002). "(Interim) Total Body Model—Status and NLG Assessment," Presentation at NLW Risk Characterization Workshop, February 21-22, 2002.*

# 4. Head Injury

As part of MRMC-NHTSA relationship, Jaycor developed a biomechanically based, skull fracture criterion, measured by existing and innovative instrumentation and validated by surrogate test data.

## 4.1 Biomechanically Based Skull Fracture Correlates

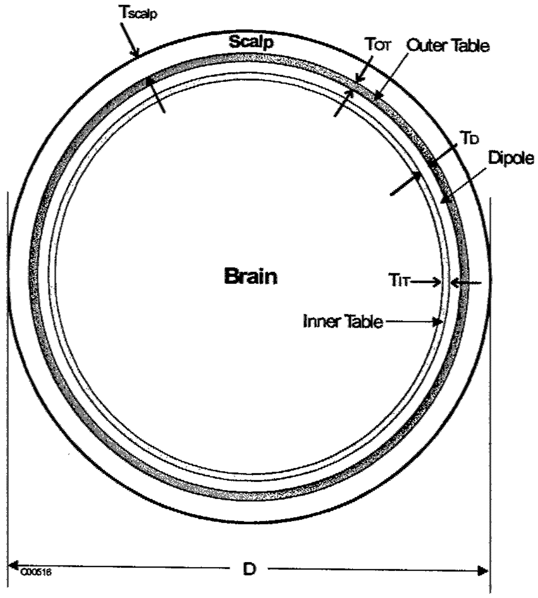
A biomechanically based criterion for impact skull fracture, expressed in terms of physical model measurements, was developed by Jaycor. Drop tests were conducted using a Hybrid III headform to generate both kinematic and dynamic data. These tests, which vary both the impact surface curvature and hardness, correspond to previously conducted cadaver tests. Time histories of force, acceleration, and impact area were measured. To obtain biomechanical data, skull strain was obtained from a simplified finite element model of the head containing a scalp; a homogenous brain; and most importantly a three-layered skull with an inner table, diploe layer, and an outer table. Logistic regression analysis was used to generate correlations between the previously observed fractures of cadaver skulls, the parameters measured in the Hybrid III headform tests, and the calculated tensile strain.



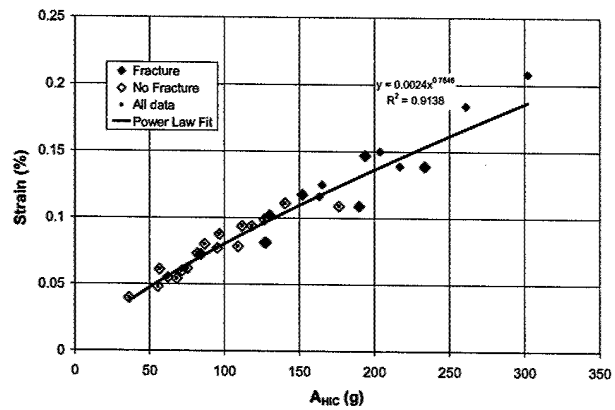
**Hybrid III Drop Test Setup**

This work leads to three potential correlates to skull fracture for crashworthiness protection. They are: (1) HIC, (2) HIC corrected by area, and (3) SFC. HIC alone does not account for target compliance. Since measuring the impact area in a car crash test is currently impractical, SFC becomes the recommended correlate. The generalized acceleration SFC has several advantages.

1. It is consistent with the fundamental biomechanical measure of skull fracture, the tensile strain.
2. It accounts for hard and soft impact partners.
3. It is easily calculated as a byproduct of calculating HIC, i.e. $SFC=\Delta V_{HIC}/\Delta t_{HIC}$.
4. It has a physical interpretation as an effective acceleration.




**Simplified Biomechanical Head Model**




**Correlation of SFC to Strain**

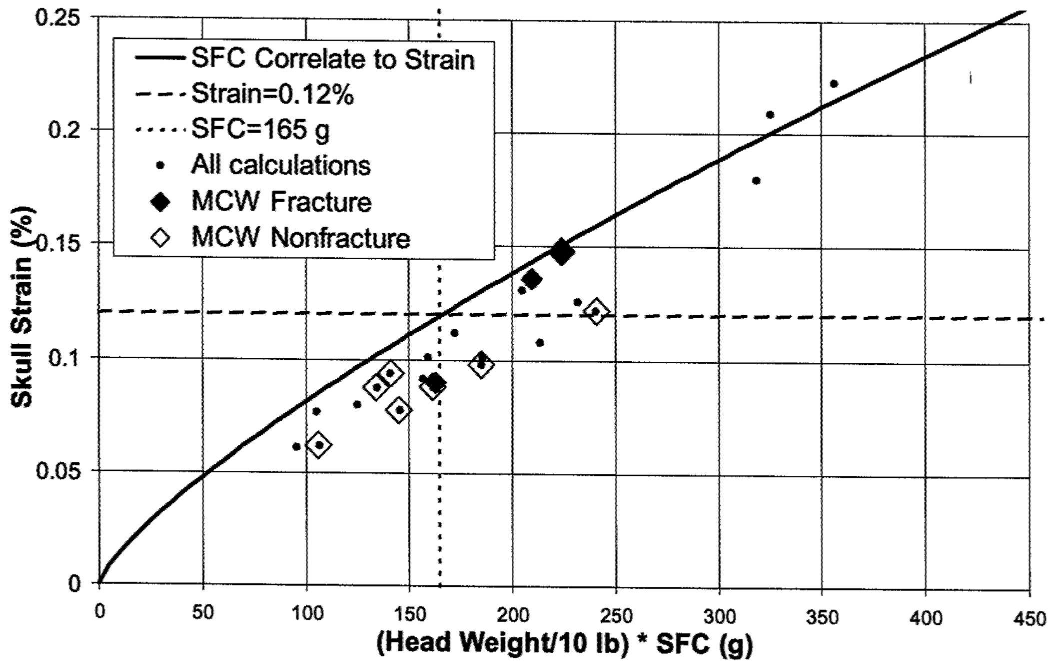
*Product 18. Vander Vorst, M.J. (2002), "Biomechanically Based Skull Fracture Correlates," Jaycor Report J2997.103-02-174 (in review).*

## 4.2 Analysis of Medical College of Wisconsin Data

Using cadaver test results from the Medical College of Wisconsin (MCW), Jaycor extended the Skull Fracture Correlate, SFC, to adult heads of varying weight. The 50% probability of skull fracture occurs at an SFC of 165 g. In order to validate SFC for a range of targets not included in its development, MCW performed drop tests of unembalmed disembodied cadaver heads against both hard and soft neoprene rubber sheets. In their tests many of the cadaver heads were significantly lighter than the nominal 10 lb head, $M_0$, used in the development of SFC and they subsequently fractured at higher levels of SFC than predicted. Jaycor calculated the tensile strain from the Simple Head Model using head weights and drop conditions corresponding to the MCW tests. Comparison of SFC with strain reveals that scaling SFC by the head mass, M, is a correlate to adult skull fracture over the range of head weights encountered in both the MCW and earlier cadaver tests. This leads to the skull fracture criterion,

$$SFC(M) < (M_0/M) *165,$$

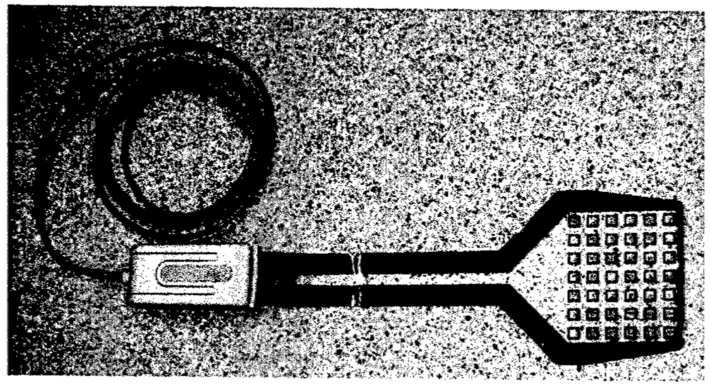
for the 50% probability of skull fracture as a function of head weight.

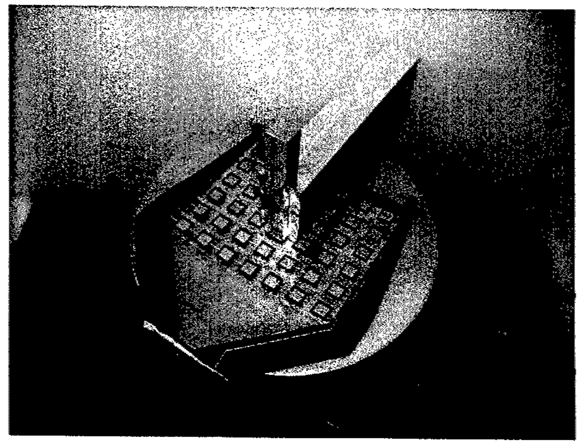



**SFC Normalized by Head Weight vs. Strain.**

*Product 19. Vander Vorst, M.J (2002). "Analysis of MCW Test Data," Jaycor Technical Report (in review).*

## 4.3 Pressure and Impact Area Instrumentation





Jaycor developed a test device and software to perform dynamic calibration and interpretation of TekScan data. TekScan instrumentation measures the transient pressure distribution at a sample rate of up to 10,000 Hertz. The instrument used in the Hybrid III drop tests has a sensor grid of $6 \times 7$ sensing elements over a total area of $3 \times 3.5$ inches. Calibration of TekScan sensors using TekScan's static methodology produced total forces, as measured by TekScan, that were far different from those measured by a force gauge. Jaycor developed a test device and associated software to calibrate each sensing element under a dynamic load. Since the 10 kHz TekScan sensor covers an area which in some cases is smaller than the total impact area, software was developed to calculate the pressure distribution assuming that, for each frame, it is in the form of a Gaussian distribution. Using Jaycor's calibration method and data interpretation software, the TekScan instrumentation now measures dynamic pressure distributions during an impact that agree with force gauge measurements.

*Product 20. Vander Vorst, M.J. (2002), "Calibration and Interpretation of Tekscan Sensors," Jaycor Technical Report 2997.103-02-184 (in work).*

*Product 21. Vander Vorst, M.J. and Long, D.W., TekScan2Jif and Tscalibrate computer programs (Jan. 2002).*

*Product 22. Vander Vorst, M.J. and Ho, K., Dynamic calibration test device for high-speed TekScan (Jan. 2002).*

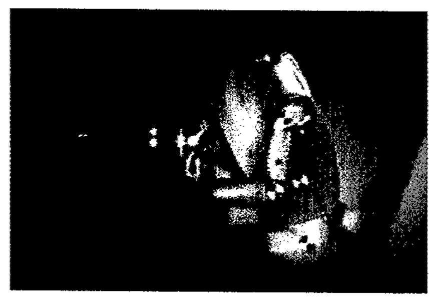
# 5. Air Bag Dynamics

A pneumatically driven Airbag Test Simulator (ATS) was developed and constructed to provide a method to conduct repeatable laboratory tests of airbag-dummy interaction. A cylindrical reservoir is pressurized by laboratory air to simulate the initial inflator energy. The pressurized reservoir connects to the airbag module through an orifice, and an aluminum diaphragm is used to hold the pressurized gas initially from discharging. Deployment is initiated by rupturing the diaphragm allowing the gas to discharge and inflate the bag from the center of the steering wheel. The ATS has been calibrated to replicate selected fleet airbag inflations. After calibration, airbag tests can be carried out without the use of the igniters with high repeatability.

The ATS has been used to qualify the head/neck responses of the advanced anthropomorphic test dummy, THOR, currently being developed by NHTSA. The THOR responses were compared against those of the Hybrid-III dummy. The dummies were tested at out-of-position 1 (OOP1) with the chin on the airbag. Data collected include head accelerations, head/neck forces and moments and chest acceleration. High-speed videos at 1000 frames/sec were also taken.

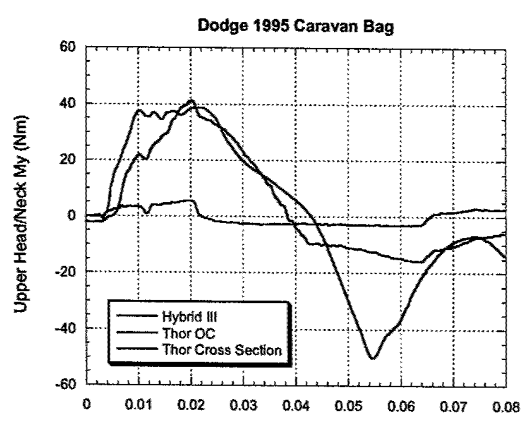
**Hybrid-III**

**THOR**

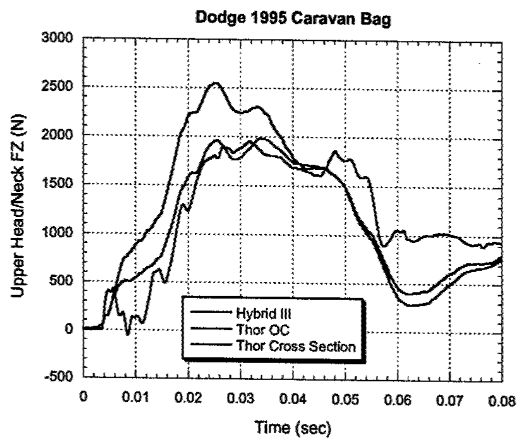


**High-speed movie showing bag deployment against THOR**

THOR is designed to distinguish the load at the occipital condyle (OC) from the total load across the entire upper head/neck cross section. It is believed that injury is primarily governed by the load at the OC that transmits true load to the cervical spine. The rest of the load is contributed from muscles that control the head/neck motion but is not an indicator of injury. In contrast, Hybrid-III

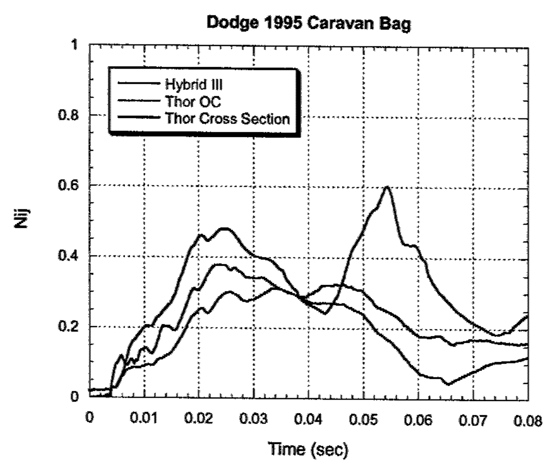


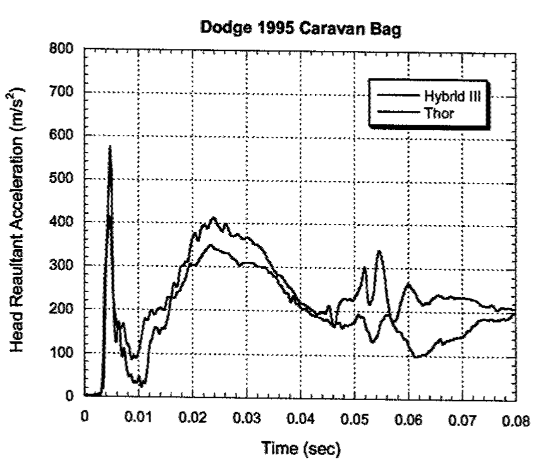
has no capability to distinguish muscle load from the actual OC joint load, and it is generally known that the Hybrid-III head/neck system is overly stiff. However, current head/neck injury criteria are calibrated using the Hybrid-III dummy.



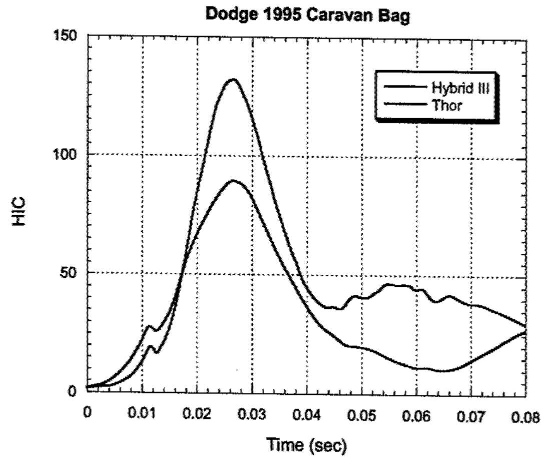

Data show that there is insignificant moment (My) at the OC joint of the THOR dummy during the entire airbag interaction process of about 80 ms. This means that the head can rotate quite easily over a significant range with little resistance at the OC joint. On the other hand, the total moment across the entire THOR upper head/neck cross-section is quite similar to the Hybrid-III up to 40 ms. After 40 ms, the THOR total upper head/neck extension (negative) moment is much smaller than Hybrid-III.

The THOR tensional force FZ at the OC is fairly similar to that of the Hybrid-III, especially during the membrane loading phase from 20-50 ms. The total FZ across the THOR upper head/neck cross section, however, is higher than Hybrid-III.




The Nij injury metrics calculated from the various test data are quite different for the same airbag. Nij is governed by the tensional force and head/neck moment. The Hybrid-III data results in the highest Nij. The THOR Nij using the OC moment is lower than that using the total cross sectional moment. From the biomechanical perspective, Nij should be calculated using the OC moment.



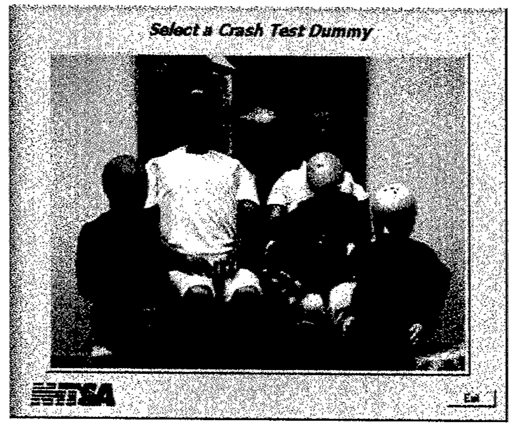

The THOR recorded lower head acceleration than Hybrid-III during both the punch out and the membrane phases. Consequently, Hybrid-III would result in higher HIC than THOR. Data overall confirm the softer nature of the THOR head/neck system than Hybrid-III making THOR more biofidelic. More work will be required to recalibrate injury tolerances if THOR replaces Hybrid-III.

*Product 23. The ATS apparatus usable by government laboratories and the automobile industry for studying airbag occupant interaction.*

*Product 24. Bandak, F. and Chan, P. C. "A Method for the Study of Close-Proximity Airbag Occupant Interactions," paper presented at the 28th Annual International Workshop on Human Subjects for Biomechanical Research, Atlanta, GA, November 5, 2000.*

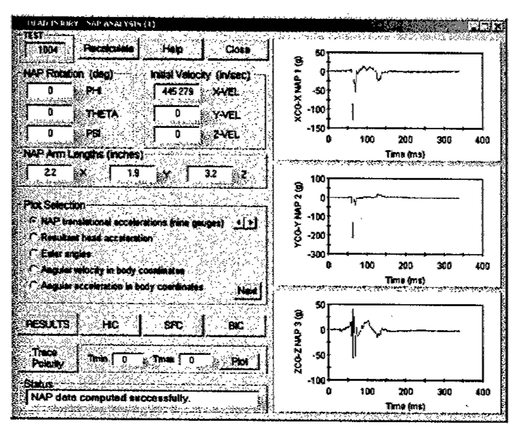
# 6. SIMon Computer Code

Over the past two fiscal years, Jaycor has developed the SIMon (*Simulated Injury Monitor*) computer code for NHTSA, a next generation (G2) tool for the assessment of bodily injury resulting from automobile collisions. The concept behind SIMon is to provide an integrated and simple-to-use mechanism to utilize recent advancements in computational techniques which can be employed to simulate human injury response. Coupled with advances in computer hardware, this brings the idea of detailed injury assessment in real-time much closer to reality. SIMon can serve as a convenient interface between a biomechanics researcher, appropriate test data of interest, and invocation of a detailed mathematical model for simulation of impact injury to a specified body region. Presently, the focus of SIMon is on head injury, but other models addressing the neck, thorax and lower extremities are planned for the future.



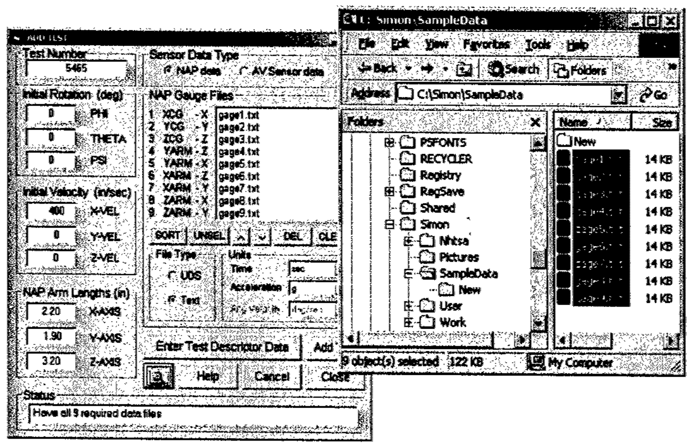

SIMon can be particularly effective in evaluating test conditions leading to possible injury during the course of research programs conducted at the various NHTSA biomechanics test centers. In addition, it can prove valuable in making assessments of the adequacy of existing injury correlations, and has a potential use by the code developer in the formulation of new relationships between potential risk factors and the extent of injury.

Recent project tasks include implementation of a model to process Nine Accelerometer Package (NAP) test data, as well as angular velocity (AV) sensing devices (e.g., MHD sensors). In the case of NAP data, nine linear accelerations along three directions are measured for the purpose of computing accurate and reliable values for rotational velocities and accelerations. These quantities play a pivotal role in the assessment of head injury. In the case of AV sensing devices, the angular velocity is measured directly, but rotational acceleration is still desired, as well as transformation from body-fixed coordinates to an inertial frame of reference. The resulting linear and rotational angular

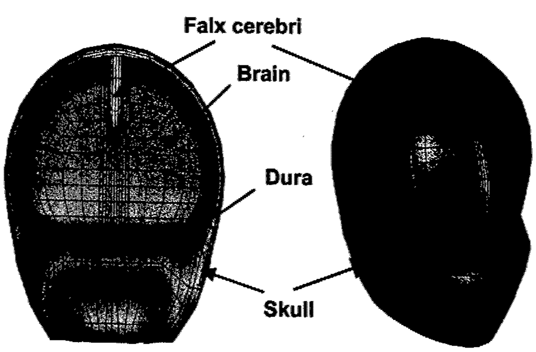


velocities constitute data for the construction of suitable load curves for a finite element model (FEM) of the human brain. This model can be invoked by SIMon, and the progress of the FE calculation, as well as graphical results, can be displayed by SIMon in real-time.

SIMon is designed to access a database either supplied by NHTSA or constructed and maintained by a user with the help of SIMon dialogs. Familiarity with database tools or software is not required. The user can easily add a test to the database by a simple drag/drop operation, referencing his/her data files from the Windows Explorer. Content of database fields of interest (such as the test number, date, test performer, etc.) can be entered directly from within SIMon dialogs. Once added, a user's test can be deleted from the database, or its database fields can be edited. Assembly and maintenance of the user database is managed entirely by SIMon. The data files that are dragged/dropped to define a test are copied into a special storage area maintained by SIMon. Hence, the original data files can be deleted at any time.



Injury assessment is made by viewing the graphical and printed data generated by SIMon for the particular model invoked. Printed output data are written to disk files saved by SIMon in an identifiable directory path.




In November 2001, SIMon 1.0 Beta was released at an annual Stapp conference workshop, and over 50 CD-ROMs were distributed to domestic and international members of the biomechanics community selected by NHTSA. The initial version of SIMon was well received. A mechanism for user feedback and code support has been established by NHTSA and Jaycor.

*Product 25. SIMon Simulated Injury Monitor Version 1.0 Beta Computer Code, Jaycor, Dr. Paul J. Masiello, November 15, 2001. Released and distributed at 2001 Annual Stapp Conference, San Antonio, Texas.*

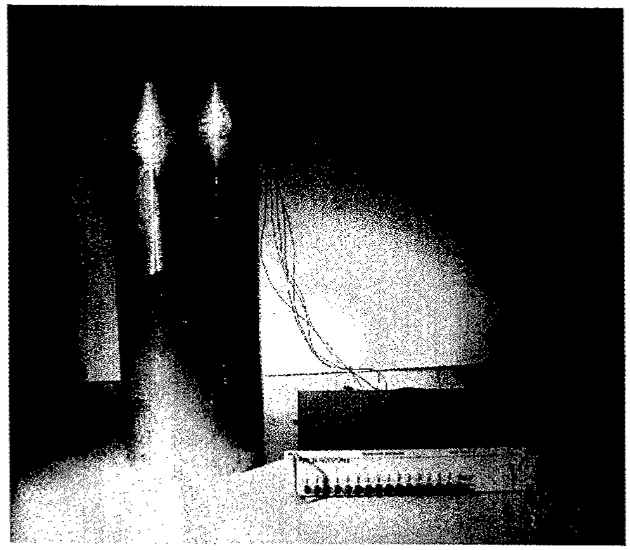
*Product 26. Bandak, F.A., Zhang A.X., Tannous, R.E., DiMasi, F., Masiello, P. and. Eppinger, R., "SIMon: A Simulated Injury Monitor; Application to Head Injury Assessment," 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Amsterdam, Netherlands, June 4-7, 2001.*

*Product 27. Kan, K.K. and Masiello, P.J., "Implementation of Euler Angles in the NAP Computational Model," Jaycor Technical Report J2997.104-02-169, February 2002.*

# 7. Thermobaric Weapon Effects

## 7.1 Blast Test Device

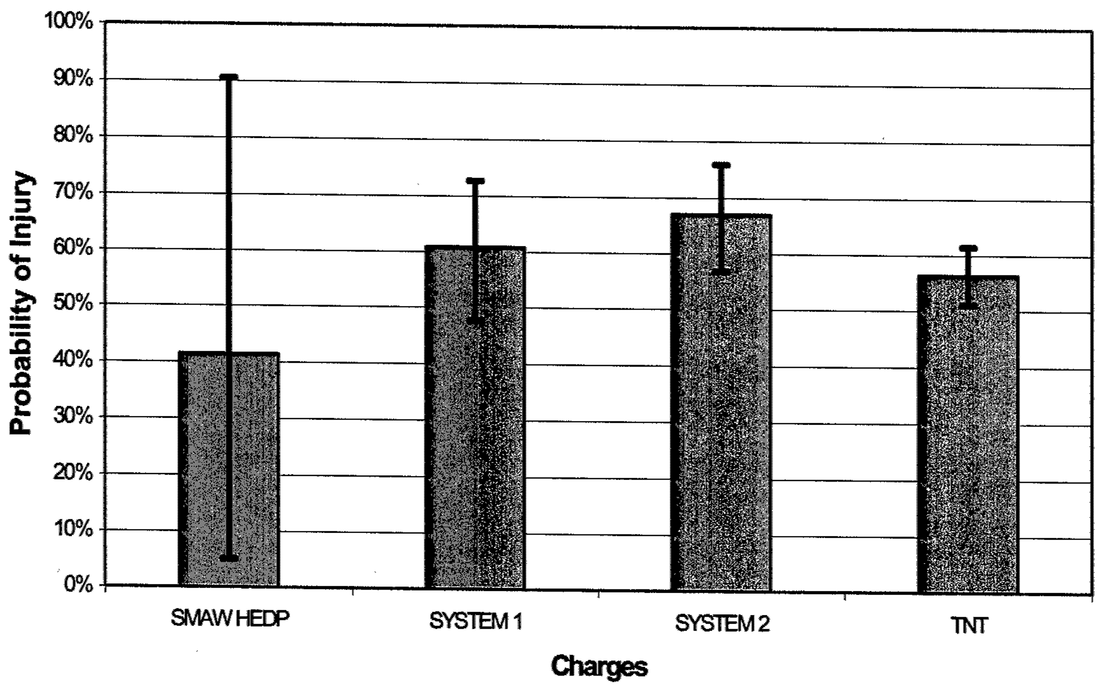
Jaycor developed a Blast Test Device (BTD) to obtain the external pressure loading similar to that on a human thorax during a blast overpressure test. The BTD is a 30 inch long, 12 inch diameter, aluminum cylinder with 0.75 inch thick walls. Four pressure transducers were screw-mounted into the cylinder with their faces flush with its surface. The pressure gauges are equally spaced about the circumference of the cylinder at a height of 15 inches. The pressure gauges, from PCB Piezotronics, incorporate a special shock isolation mount to moderate ringing transmitted from the cylinder.



**Blast Test Device and Signal Conditioner**

## 7.2 Test Support and Report

We have applied INJURY 7.1 to analyze the pressure data recorded in three BTDs in the thermobaric test conducted at the Army Research Laboratories, Blossom Point, Maryland, January 14 – 17, 2002. The results show that the charges, Systems 1 and 2, cause lung injury in a level somewhat higher than the level resulting from the reference charge TNT. On the other hand, the charge SMAW HEDP causes substantially lower levels of injury as compared to TNT. For the worst position tested (BTD 2), the level of probability of injury for Systems 1 and 2 is about 11% and 14%, respectively in the category of moderate or severe lung contusion, and is about 0.7% and 0.9 %, respectively in the category of severe lung contusion. The levels for SMAW HEDP are 5% and 0.3 % in the two categories in lung contusions, respectively. These findings were reported to the director of the program, Charles Huber at NSWC-IH.




**Probability of lung injury on the BTDs as induced by the four charges tested shows only moderate increase for the thermobaric charges, System 1 and System 2 over the reference, TNT.**

*Product 28. Kan, K.-K., and K. Ho (2002). "Analysis of Thermobaric Test Data by INJURY 7.1," Jaycor Report J2997.111-02-172.*

# 8. List of Products